# BUILDING TEMPERATURE SENSING ARRAYS (THERMOCOUPLE TREES)

## General

A temperature sensing array used in pavement research will take on many configurations depending upon the array's intended use. Some intended uses for temperature arrays include frost depth, temperature gradients in pavement layers, temperature compensation for other instruments, all of the above or any number of additional applications. Temperature arrays are often called temperature trees. For the purpose of this document the latter term will be used. This document reflects some of the methods related to building temperature measurement instruments for the pavement research environment and is based on 20 years of experience.

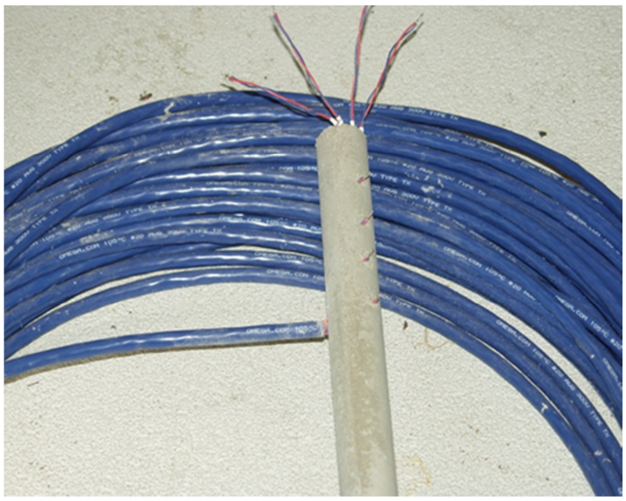

**Figure 1: Eight-Sensor Tree with PCC Body for a Composite Pavement**

The first step in building the temperature tree is to understand the need for the tree. The research proposal will provide direction or at least hints for: the duration of the research, why temperature is important, the scale to be used, the type of sensor to be used, the composition of the tree body, the precision of measurements, the number of layers to be observed, the vertical location of individual sensors, and frequency of measurements. If there is no research proposal, thought should be given to all these parameters and more.

This document assumes that a decision has been made regarding the sensor type. The tree will use Type "T" thermocouples for measuring temperature. Thermocouples are manufactured for a large number of applications, none of which fit the pavement research application. MnROAD constructs its own thermocouple sensors by twisting 20 gauge, solid constantan and copper leads together to create a rudimentary thermocouple perfect for the pavement research application.

**Figure 2: 16-Sensor Tree with a PVC Conduit Body for an HMA Pavement**

There are three components to a temperature sensing array: the sensor, the lead-in cable, and the body. The sensor is discussed above. By choosing thermocouples as our measuring tool, our lead-in cable must be type "T" thermocouple extension cable. The body of the tree may be of several materials including wooden dowels, PVC conduit, reinforced concrete, or any of several other materials. The body of the tree simply holds the individual sensors in their relative positions and provides some protection for the individual thermocouple lead wires.

The next consideration is the number of sensors needed and the total length of cable needed to connect the tree with the data collection equipment. The researcher's proposal will define

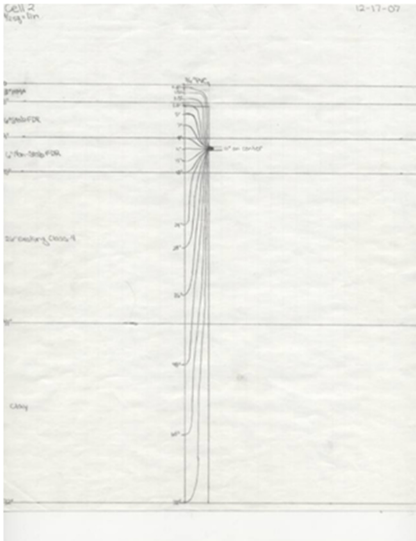

Figure 3: Scale Sketch of 16-Sensor Tree with PVC Body for an HMA Section

pavement section layers and the tree sensor's position with respect to those layers. This is necessary to determine where the lead-in cable will exit the tree and to dimension the sensor locations with respect to the top of the tree (see Table 1). To determine the length of lead-in cable, a scaled plan view of the sensor location with respect to the data collection cabinet is necessary.

The adjacent sketch, Figure 3, shows the number and position of sensors with respect to the pavement, base, and sub-base layers. For most temperature tree installations, the tree is installed from the top of the base layer, in this case a stabilized FDR. The tree body stops at the top of the base layer. The sensor leads extending from the top of the body are installed after the HMA pavement is placed (see "Installing Temperature Arrays, HMA Pavements"). The top of the tree is the reference point from which sensor locations and the lead-in cable exit location are dimensioned.

Given the expense of thermocouple extension cable, an accurate estimate of the length of lead-in cable is needed. Determining the cable length requires a scaled plan view schematic of the tree location and the location of the housing (data collection cabinet) for the data logger. In Figure 4, the plan location of the temperature tree is represented by the pentagon. Buried conduits are represented with red lines and conduit openings are shown as blue dots. The lead-in cable for the tree runs from the center of the lane to the conduit opening, through the angled conduit run to vault 10-1; from vault 10-1 to vault 10-2 and from vault 10-2 to the data collection cabinet where the data logger is housed. The horizontal length of this run is 70 feet. Add five-feet of slack in each vault and 10-feet for cable management in the cabinet and the length is now 90 feet. Finally, add 15 feet for vertical risers and the length of cable in the tree itself and the length is 105 feet.

Now that the length of cable and the dimensions for the sensor positions are determined, the tree construction may begin.

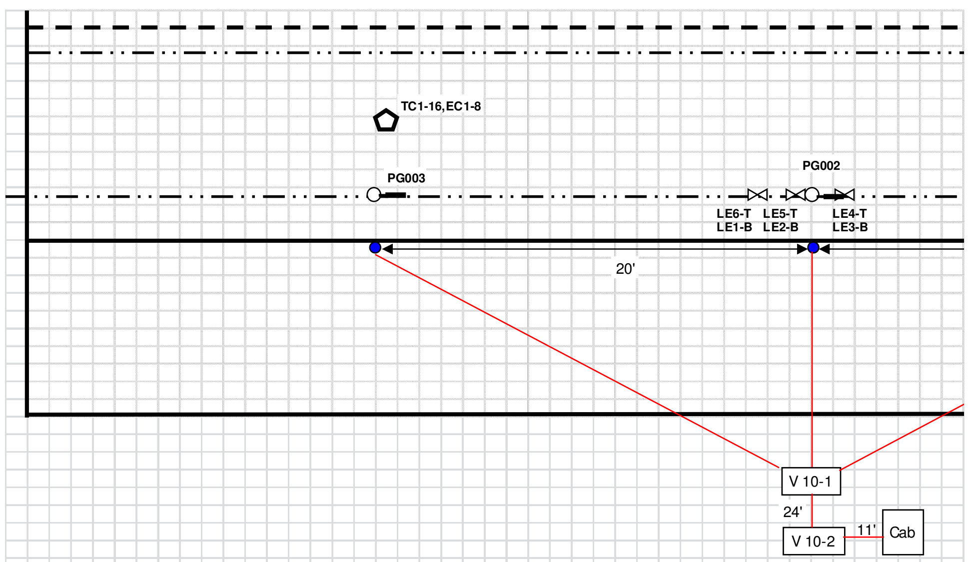


Figure 4: Scaled Plan View Sketch of Instrumented Section

## Constructing the Temperature Tree

As mentioned in the General section, there are three components for a temperature tree: the sensor, the lead-in cable, and the body. This temperature tree is to be constructed with one-inch diameter PVC (polyvinyl chloride) conduit as the body. From information in the scale sketch in Figure 3 Table 1 may be prepared. The table shows the individual thermocouple elevations with respect to the pavement surface as well as to the top of the tree body. This table will provide direction for preparing the tree's PVC body for assembly.

**Table 1: Sensor Position and Material**

| TC # | Inches from Surface | Inches from TC-Body Top | Comment |
|---|---|---|---|
| **1** | -½ | -3 | HMA Pavement Near Surface |
| **2** | -1½ | -2 | Mid-Pavement |
| **3** | -2½ | -1 | HMA Pavement Near Bottom |
| **4** | -3½ | 0 | ½-Inch from Top of Base |
| **5** | -5 | 1½ | Mid-Base Layer |
| **6** | -7 | 3½ | Mid-Base |
| **7** | -9 | 5½ | Near Bottom of Base |
| **8** | -11 | 7½ | Sub-Base, Near Top |
| **9** | -13 | 9½ | Mid-Sub-Base |
| | -13 | 9½ | Lead Exits Tree Body |
| **10** | -15 | 11½ | Bot. Sub-Base/Top Granular |
| **11** | -24 | 20½ | Mid-Granular Sub-Base |
| **12** | -28 | 24½ | Mid-Granular Sub-Base |
| **13** | -36 | 32½ | Mid-Granular Sub-Base |
| | -43 | 39½ | Gran. Sub-base/Clay Interface |
| **14** | -48 | 44½ | Clay Sub-Grade |
| **15** | -60 | 56½ | Clay Sub-Grade |
| **16** | -72 | 68½ | Clay Sub-Grade |

## Preparing the PVC Body for Assembly

Preparing the body is a two-step process: cutting the PVC conduit to length and drilling the holes for the sensors and lead-in cable.

PVC electrical conduit has a bell end for joining segments of conduit together. The bell end will be the bottom of the tree body. The bell is typically three-inches long. PVC conduit comes in 10-foot lengths; the cut end will be the top of the tree. The length of the tree, for the example in Figure 3 and Table 1, will be 68½-inches plus the 3-inch bell or 71½-inches long.

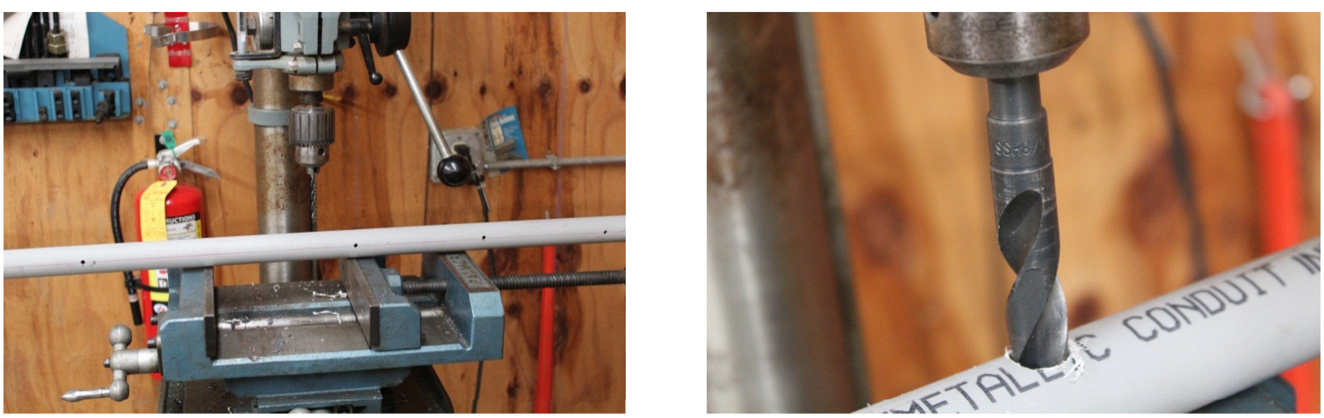

**Figure 5: Drilling Sensor and Lead-in Holes**

The second step for preparing the tree body is drilling the sensor holes and the hole for the lead-in cable. Use a ¼-inch drill bit for the sensor holes and a ⅝-inch drill bit for the lead-in cable hole. The lead-in cable hole is 180 degrees or opposite the holes for the sensors. De-burr the holes and the temperature tree body is ready for assembly.

## Preparing the Thermocouple Extension Cable for Assembly

Preparing the 32-conductor (20 gauge, single conductor, 16-pairs; one copper, one constantan), thermocouple extension cable for assembly is next. The thermocouple extension cable consists, from inside out, of: a central strength member, 16-twisted pairs, a clear plastic vapor barrier, a drain wire, aluminum foil-backed Mylar shield, a Kevlar rip-cord, and a blue PE (polyethylene) outer jacket. There are three steps in preparing the thermocouple extension cable for tree assembly: exposing the conductors, relabeling the pairs, and isolating individual pairs to be installed above the lead-in hole from those to be installed below the lead-in hole.

**Figure 6: Exposed Conductor Pairs**

Exposing the conductors requires removal of the jacket, rip-cord, shield, drain wire, and vapor barrier. Compute the length of exposed conductors by subtracting the location of the lead-in hole (9½-inches from tree top, see Table 1) from the bottom sensor location (68½-inches) and adding six-inches for ease-of-installation. That is 65-inches of exposed conductors; mark the outer jacket. With a utility knife, carefully circumscribe the outer jacket at the mark. Use the rip-cord to split the outer jacket lengthwise; using a utility knife to longitudinally split the jacket will likely damage the conductor insulation. A cable stripping tool may be used to remove the outer jacket.

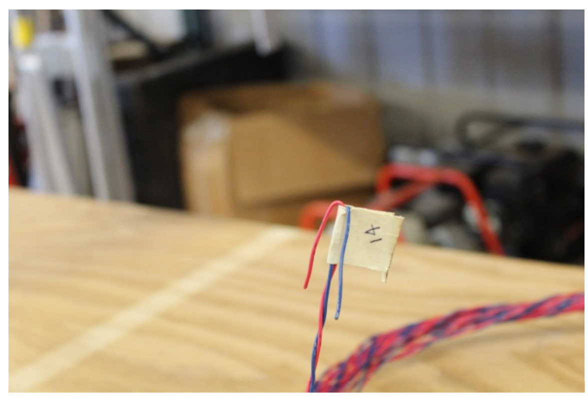

**Figure 7: Label Individual Pairs for Convenience**

Each conductor pair is numbered. Each wire of a pair has the same number. The numbers on the wire insulation are quite small and hard to read without a magnifier. Arabic numerals are followed by English spellings. Isolate the individual pairs and re-label the pairs so they are easily identified.

The final step in preparing the thermocouple extension cable for assembly is to unwind the individual pairs and organize them. The Individual pairs are helically wound about the central strength member in groups. Carefully separate the individual pairs for the entire length of the exposed conductors. Individual pairs must remain twisted at seven twists per foot to counteract the effects of EMI (electro-magnetic interference).

**Figure 8: Separate and Organize Pairs**

There are no preparatory steps for the sensors prior to assembly other than to be mindful that the single-conductor wires have small diameters (20 gauge) and the conductor is soft and easily broken.

## Assembling the Temperature Tree

Assembling the tree seems simple; put the individual pairs in their respective holes and fill the body with urethane. The reality is that tree assembly can be frustrating and very time consuming without a detailed process and patience. First, clamp the tree body to the surface of a high workbench with the lead-in hole facing away and the sensor holes facing toward you. Put the cable on the bench such that the cable end of the individual pairs is within four-inches of the body lead-in hole. Organize the individual pairs with the pairs above the lead-in hole to one side and those below the lead-in hole to the other. Be sure that the pairs are separated all the way back to the point where the jacket and other protection have been removed.

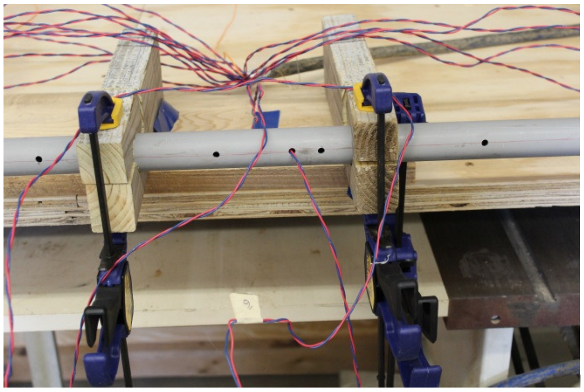

**Figure 9: Inserting Wires in the Body Above the Lead-In-Hole**

Work on the pairs above the lead-in hole first. Start with the sensor closest to the lead-in hole. In the case of our example (see Table 1), that would be pair # 9. In the adjacent Figure 9, the lead in hole is facing away and is just to the left of the inserted pair (pair # 10) in line with the blue tape on the bench top. The adjacent illustration shows pair #9 as the next pair to be installed because it's a different tree. Notice the individual pairs separated left and right and no tangles at the cable end. As you are inserting the individual pairs through the lead-in hole, try to keep the already inserted pairs as close to the front face of the body as possible. This will maximize the amount of room available for inserting successive pairs. Once all the pairs above the lead-in hole are inserted, take all the slack out of the wires within the body and prepare to install the pairs below the lead-in hole.

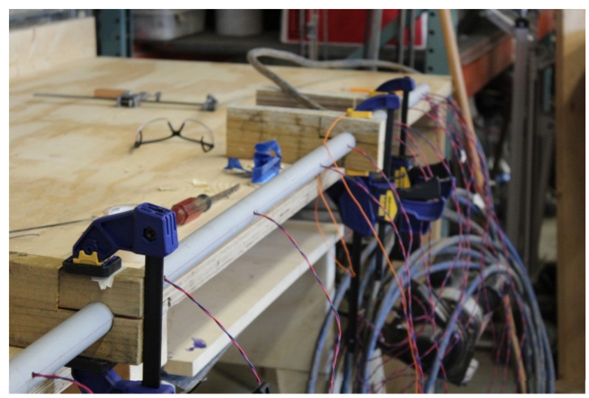

**Figure 10: All the Sensor Pairs in Position**

Installing the wires below the lead-in hole is more difficult as longer lengths of wire within the body make hitting the sensor holes more difficult. Often a hook will be necessary to "fish" the wires from the body and out of the sensor hole. A "pull wire" may be utilized as an alternative method for getting the wire pair into the sensor hole. Now that all the pairs are in their assigned positions the task of taking the slack out of the wire pairs, inside the body of the tree begins. This is an iterative process as we do not want to put too much strain on the small diameter, soft-metal conductors.

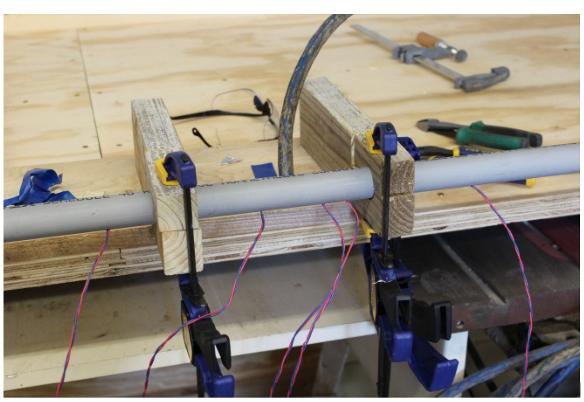

**Figure 11: Cable-end Jacket Inside the Tree Body**

The objective of this step is to get the jacketed portion of the cable-end (see Figure 9 for the before condition) within the body cavity such that when the body cavity is filled with Urethane resin all the individual pairs within the body cavity are encapsulated in a water proof environment. As mentioned above this is an iterative process. Push the cable-end as close to the lead-in hole as possible and then pull the slack from the individual leads. Three or four iterations will be needed to achieve the product shown in Figure 11; that is the cable jacket is well inside the tree body. Remove all the slack from the individual pairs such that all the individual pairs are lying flat on the interior wall adjacent to the sensor openings.

Prior to filling the body cavity, test the sensor leads for conductivity. With all the pulling and bending of the wires in the assembly process, breaking a wire without noticing is a possibility. If there are no breaks in the wires continue with the assembly process.

The last step in tree assembly is filling the body cavity with urethane resin. To prepare the body for the resin, all the sensor holes, the top and the lead-in hole have to be sealed. MnROAD uses electrical tape and small amounts of duct seal to prevent leakage of the semi-viscous urethane resin. Place a small amount of duct seal around the wires in each of the sensor holes and around the lead-in cable and around the wires exiting the top. Use electrical tape to finish the sealing job. The larger the hole the more tape is needed to seal. The bottom of the PVC conduit (body) has a bell end which works nicely as a funnel for the resin. With all the holes sealed, the last bit of preparation necessary is to fix the body on an angle so that when the resin is being poured into the body the air bubbles can escape.

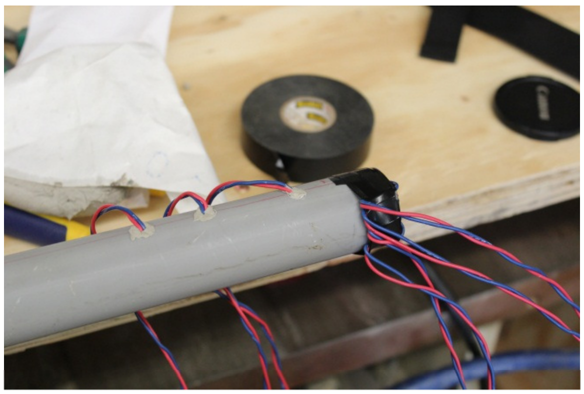

**Figure 13: Sealing the Holes**

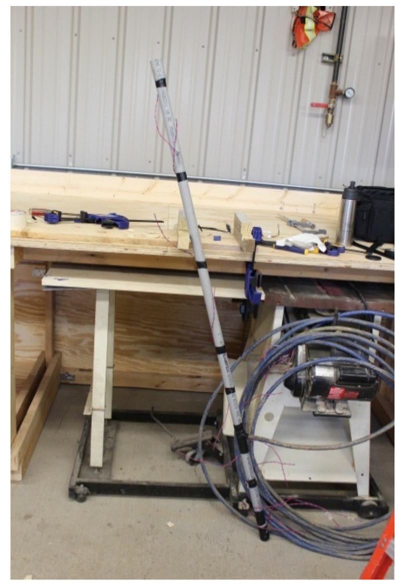

**Figure 12: Tree Body Prepared for Resin**

Preparing the urethane for filling the tree cavity is also necessary. MnROAD uses Pro-Cast 20 modeling urethane for its physical characteristics and ease of use. It is a two-part urethane mixed 50:50. Two paint mixers and two graduated containers will be needed to prepare the resin and hardener for mixing.


**Figure 14: Pro-Cast Components, Tools, and Containers**

Particulates in the resin and hardener will have settled out over time and they will have to be re-suspended prior to mixing the resin and hardener. This is best done with a power mixer as the particulates are very dense when settled out.

**Figure 15: Pro-Cast Resin with Separated Particulates**

Dedicate a mixer for each of the two components; resin and hardener. Mix each of the components thoroughly to ensure a quality casting and a mixture that hardens uniformly.

Re-suspending the particulates will take a lot of time. Be patient and be sure that all the lumps are remixed with the component matrix. Once remixed, the particulates in the resin and in the hardener will remain suspended for at least an hour so remixing is usually not necessary to the completion of the project.

Calculate the amount of each of the components needed to fill the body of the tree. There will be a little leakage so be sure to mix enough of the components to completely fill the cavity. Use a metric measure to calculate the volume of the cavity; this tree will require just under a liter of resin and hardener combined. Add 15-percent to the volume for leakage and you are ready to mix the resin and hardener.

**Figure 16: Measured Resin and Hardener**

Pour one-half liter resin in one graduated container and one-half liter of hardener in the other graduated container. If there are multiple trees to pour, slightly less hardener may be used to prolong the time to set (this requires experimentation to determine set times).

The tree body (PVC conduit) is quite tall. A step ladder may be needed to control the speed at which the urethane is poured into the tree body.

**Figure 17: Tree Cavity Filled**

Mix the two components together in another container large enough to hold both components and allow gentle mixing with a clean paint stick. Mix the components thoroughly and fill the tree cavity immediately. Pour the mixture into the cavity slowly to minimize turbulence in the fluid and the creation of air bubbles. Also so that the air bubbles, if they do form, have time to come to the surface of the mixture. Expect some leakage but do not worry about it if you did not reduce the hardener component significantly. The urethane will harden within an hour.

When the urethane is hardened, the tape and duct seal are removed. The tree is now assembled and ready for the sensors to be formed.

## Forming the Sensors

Forming the sensors is the simple process of twisting the copper and constantan conductors together and soldering the junction. Some would say that soldering the junction changes the character of the dissimilar metal junction and thereby the Seebeck Voltage generated. MnROAD has not found this to be the case. In testing of soldered versus unsoldered junctions, no discernable differences were noted. Given that this instrument will be buried under the pavement corrosion will take its toll on unsoldered junctions and MnROAD's experience is that the thermocouple will not last more than a few months if the wire junction (thermocouple) is not soldered.

To form the sensors, cut the wires off approximately one-inch from the body. Strip the insulation from the conductors as close to the body as possible. Twist the conductors tightly being careful to not break the conductors; the wires will break of twisted too tightly and if you break them now, the sensor is lost. Clip the "rabbit ears" from the wires and solder the entire length of the twisted wires. The length of the sensor is approximately ½ to ¾-inch long. The sensor may be shortened but remember that good contact with the material (soils) surrounding the sensor is desired.

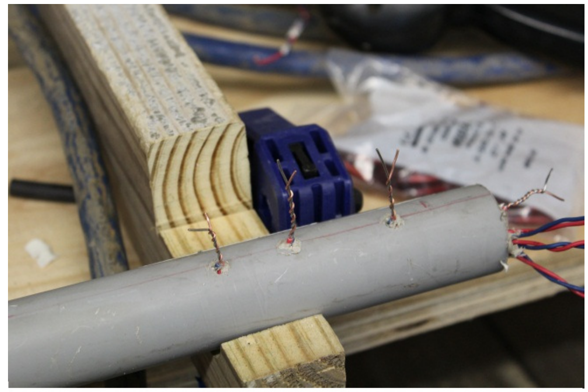

**Figure 18: Forming the Sensors**

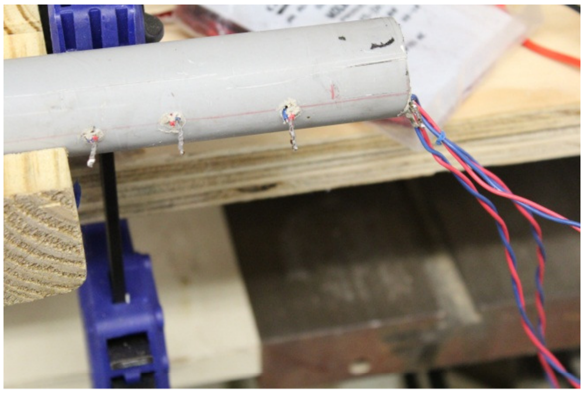

**Figure 19: Soldered Sensors**

For those sensors extending from the top of the tree (usually the sensors to be used in the HMA pavement, these are intended for a pervious paver installation), be sure to leave adequate length for them to be placed in the position desired. Strip the insulation from the last inch of the conductors. Wrapping the individual pairs with electrical tape may offer some additional protection. Twist the bare conductors together, solder, and cut the sensor to length.

The thermocouple temperature tree is now ready for testing and installation.

## Testing the Thermocouples


**Figure 20: Continuity Testing**

Prior to installation, test the individual sensors for continuity. That is, connect the multi-meter probes to the red and blue wires for each of the sensors. For this length of wire, the resistance measured should be approximately 26 Ohms. Varied lengths of wires will yield slight differences in the resistance measured on each of the probes.

As you probably noticed when checking continuity on individual wires (prior to filling the body cavity), copper is far more conductive than constantan. Constantan has a much higher resistivity than copper.

Testing for measurement precision requires a temperature controlled medium (e.g. ice water bath). You may want to use a thermocouple tester for this process.